Precision Tests of Fundamental Interactions with the LBNE/LBNF Near Detector

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HIGH RESOLUTION NEAR DETECTOR FOR LBNE/LBNF

✦ *The Long-Baseline Neutrino Experiment/Facility (LBNE/LBNF) designed for high sensitivity measurements of Long-Baseline (LBL)* $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ *oscillations with* $\nu_e(\bar{\nu})$ *appearance and* $\nu_\mu(\bar{\nu}_\mu)$ *disappearance* (LBNE Collaboration, arXiv:1307.7335 [hep-ex])

- *High intensity* ν *and* $\bar{\nu}$ *beams from Fermilab to Homestake mine in SD* ($L \sim 1300$ *km*)
- *Look for CP violation, neutrino mass hierarchy, searches beyond PNMS, etc.*

✦ *Need a high resolution near detector (ND) complex to address LBL systematics:*

- *Beyond the naive "identical" paradigm;*
- *Measurement of* $\nu_\mu, \bar{\nu}$, $\boxed{\nu_e}$, $\boxed{\bar{\nu}_e}$ *content vs.* E_ν *and* θ_ν;
- *Measurement of* ν*-induced* $\pi^\pm/K^\pm/p/\pi^0$ *in CC and NC interactions;*
- *Quantitative determination of* E_ν *absolute energy scale;*
- *Measurement of detailed event topologies in CC & NC.*

$\Longrightarrow$ *Provide an 'Event-Generator' measurement for LBL*

✦ *A fine grained near detector operating in the LBNF (anti)neutrino beam is a natural candidate to study neutrino scattering physics.*

Can it achieve a substantial physics potential for non-oscillation physics?

REQUIREMENTS FOR $\nu(\bar{\nu})$ SCATTERING PHYSICS

✦ STATISTICS

- *Limiting factor for old experiments*;
- *Need increase* $\times 10 \div \times 100$ *with respect to current/past experiments;*
- *Detector mass not critical at the LBNF due to the large fluxes;*

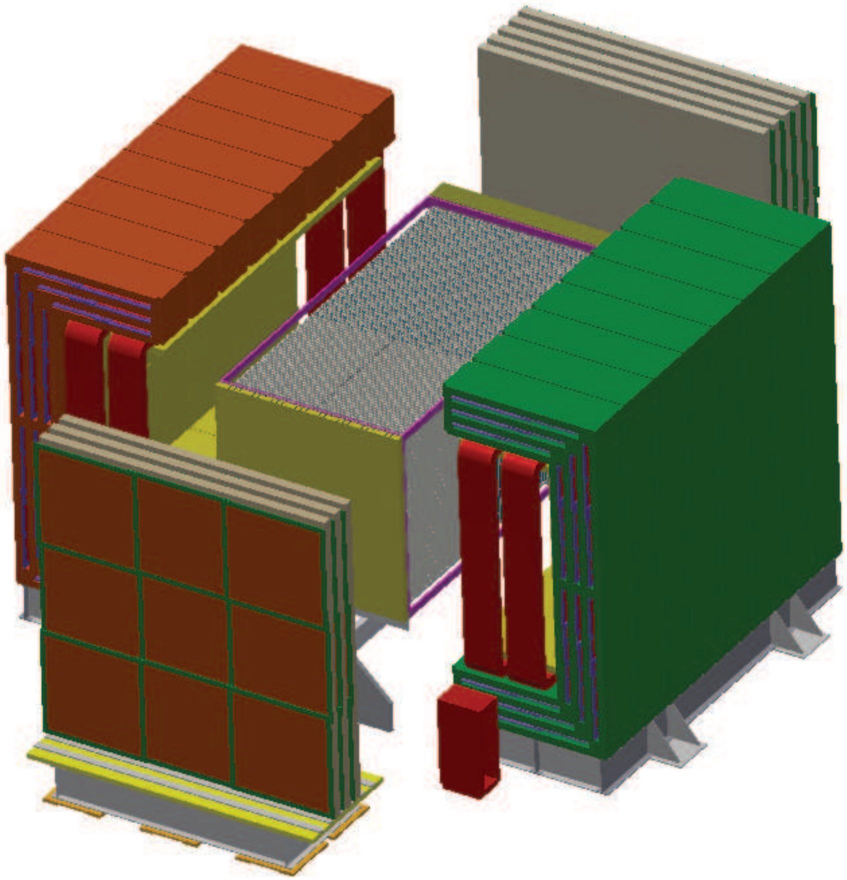
$\Longrightarrow$ *Shift focus from measurements of cross-sections to precision tests of foundamental interactions & structure of matter*

✦ *Reduction of systematic uncertainties:*

- *Flux, energy & momentum scales, backgrounds, theoretical modeling etc.;*
- *Start to limit current ν-scattering experiments*;
- *Need fine-grained detectors &* REDUNDANCY *through multiple measurements*

$\Longrightarrow$ *A major physics program requires* HIGH RESOLUTION

LBNE/LBNF NEAR DETECTOR



Based upon the NOMAD concept/experience

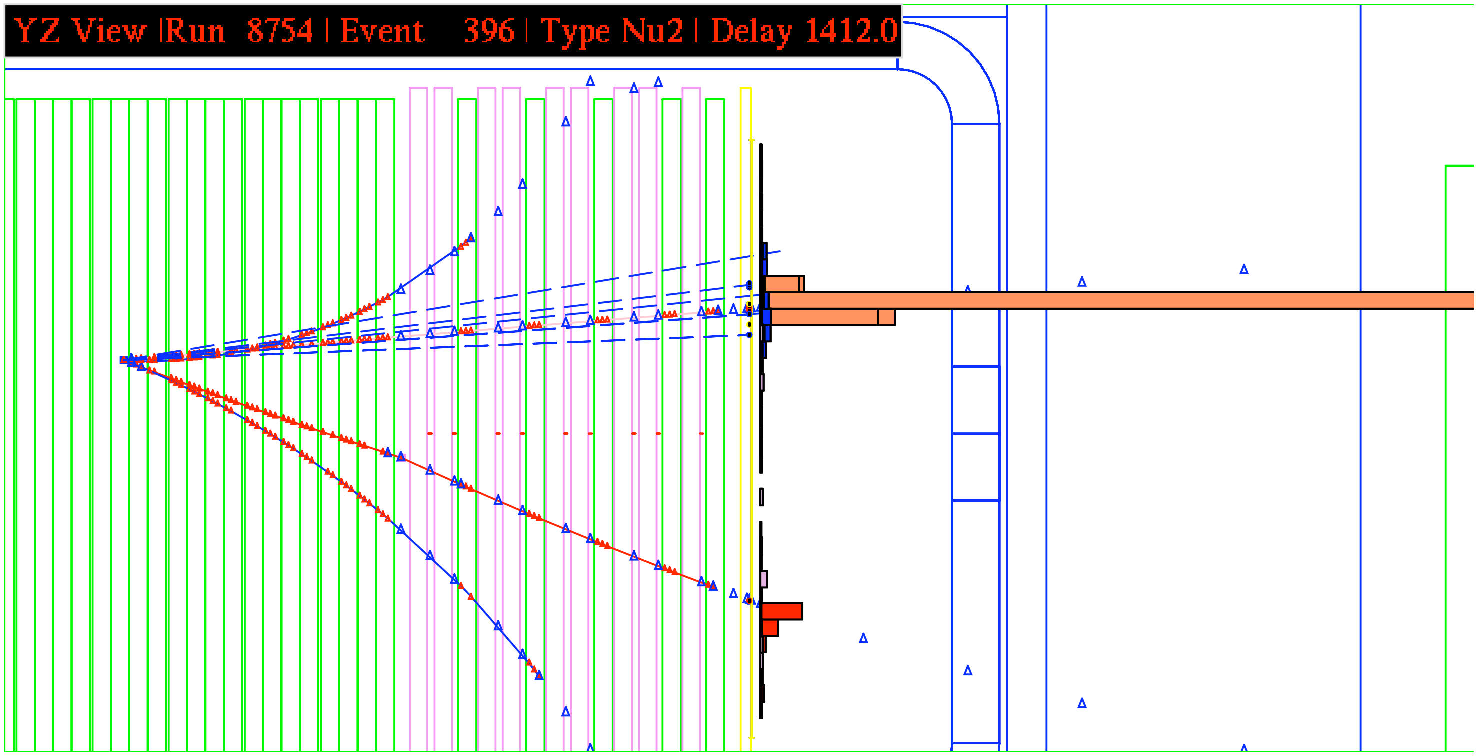
- *Straw Tube Tracker* 3.5m×3.5m×6.5m ($\rho \sim 0.1\ g/cm^3$) *with target embedded*
- Target mass ∼7t: $(C_3H_6)_n$,C,Ar,Ca,etc.
- 4π ECAL in dipole B field (0.4 T)
- 4π μ-Detector (RPC) in return yoke and downstream
- Pressurized Ar target $\sim \times 10$ FD Stat.
- *Precise measurement of 4-momenta*

- *Combined tracking and particle ID*
- Transition Radiation $\Longrightarrow e^-/e^+$ ID, γ
- $dE/dx \Longrightarrow$ Proton ID, $\pi^{+/-}$, $K^{+/-}$
- Magnet/Muon detector $\Longrightarrow \mu^+/\mu^-$

LOW-DENSITY "ELECTRONIC BUBBLE CHAMBER"

$\bar{\nu}_e$ Charged Current

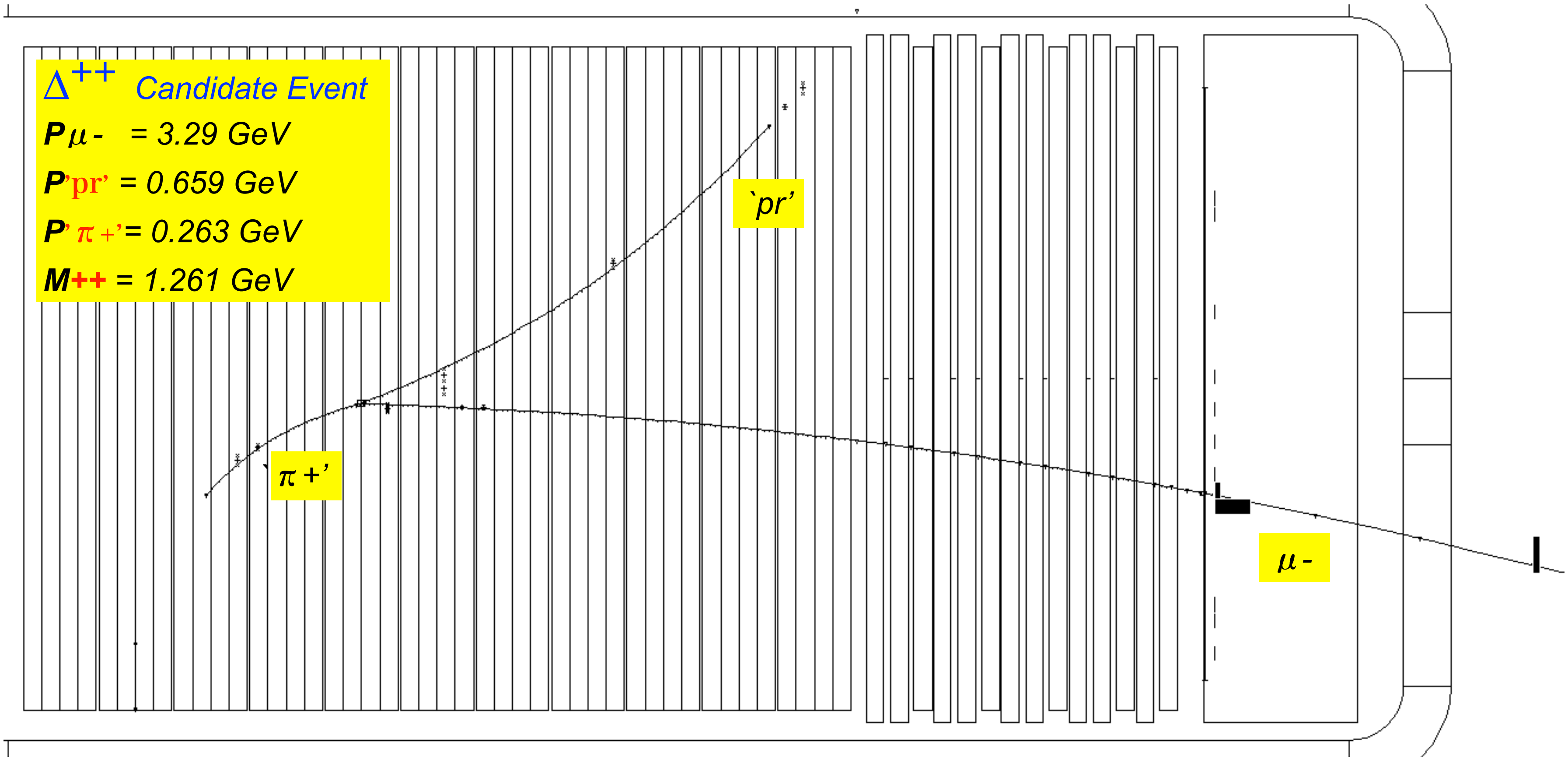
e^+ reconstruction & ID



Event candidate from NOMAD data $\Longrightarrow$ STT has $\times 10$ granularity

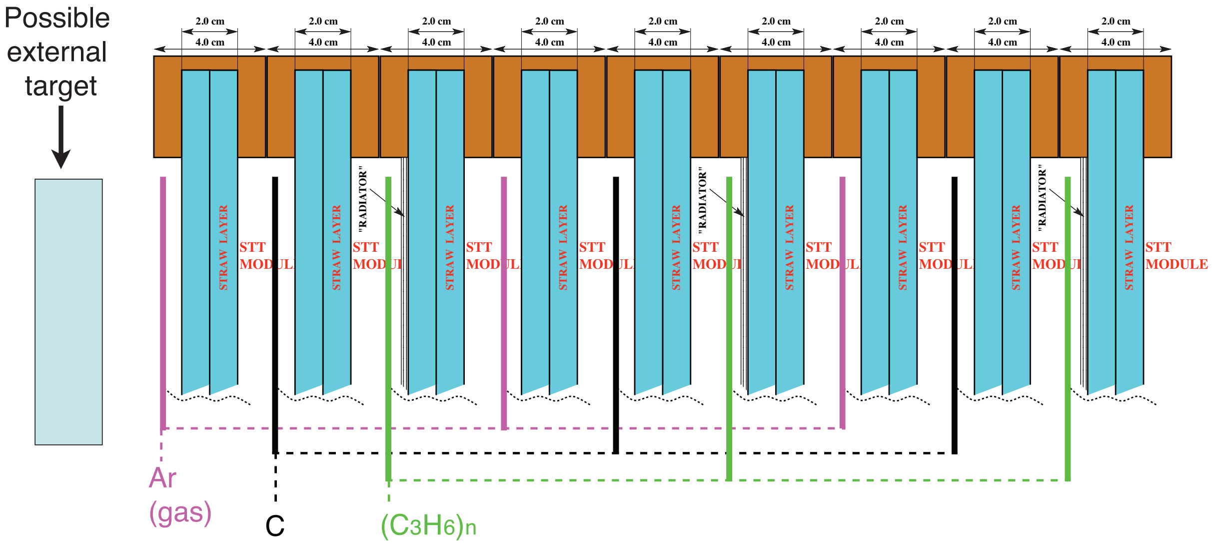
$$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- p \pi^+$$

p reconstruction & ID
wide angle hadrons



Event candidate from NOMAD data $\Longrightarrow$ *STT has* $\times 10$ *granularity*

NUCLEAR TARGETS



MAIN target $(C_3H_6)_n$ radiators: fiducial mass ∼5t

- *Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, H_2O, D_2O, etc.*
  $\Longrightarrow$ *Separation from excellent vertex ($\sim 100\mu m$) and angular (< 2 mrad) resolutions*

- *Subtraction of* C TARGET *(0.5 tons) from polypropylene* $(C_3H_6)_n$ RADIATORS *provides* $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)$ $\nu(\bar{\nu})$ *CC interactions on free proton*
  $\Longrightarrow$ *Absolute $\bar{\nu}_\mu$ flux from QE*
  $\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*

- *Pressurized* Ar GAS *target (∼ 140 atm) inside Al/C tubes and solid* Ca TARGET *provide detailed understanding of the FD $A = 40$ target*
  $\Longrightarrow$ *Collect $\times 10$ unoscillated FD statistics on Ar target*
  $\Longrightarrow$ *Study of flavor dependence & isospin physics*

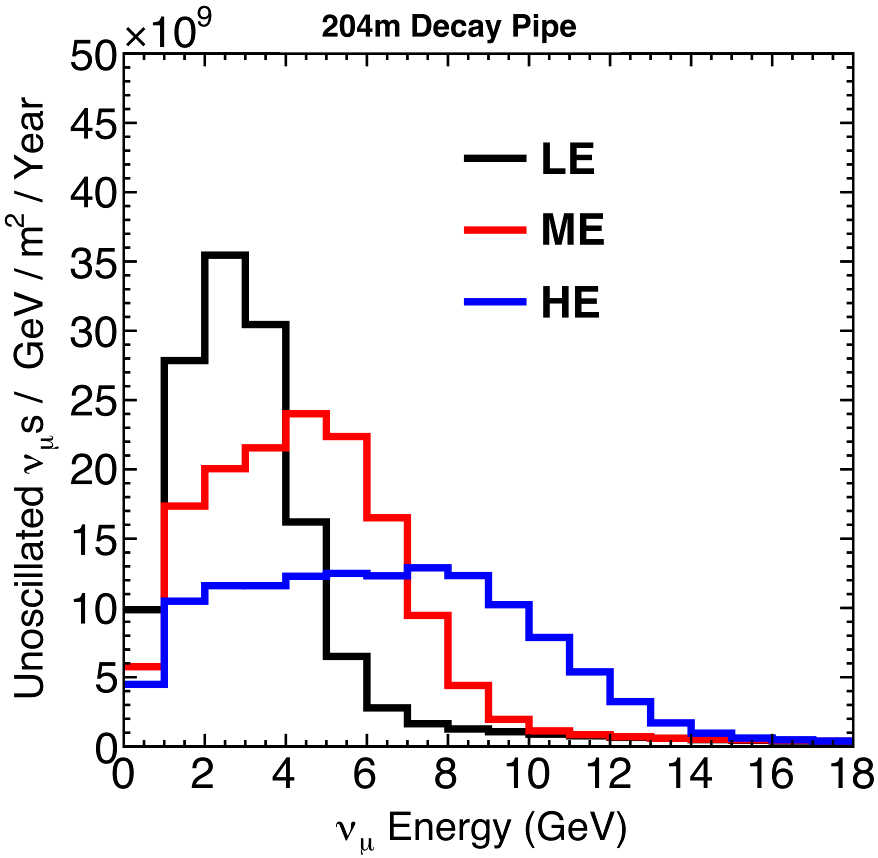
BEAM AND EVENT RATES

- *New high intensity (PIP-II) 1.2 MW proton beam at $E = 120$ GeV delivering 11×10^{20} pot/year for 5 (ν)+5($\bar{\nu}$) years*

  $\Longrightarrow$ *Upgradable to 2.4 MW*

- *Different energy tuning possible*

- *At ND location (459m from proton target) expect to collect $90(40) \times 10^6$ $\nu_\mu(\bar{\nu}_\mu)$ CC inclusive interactions*



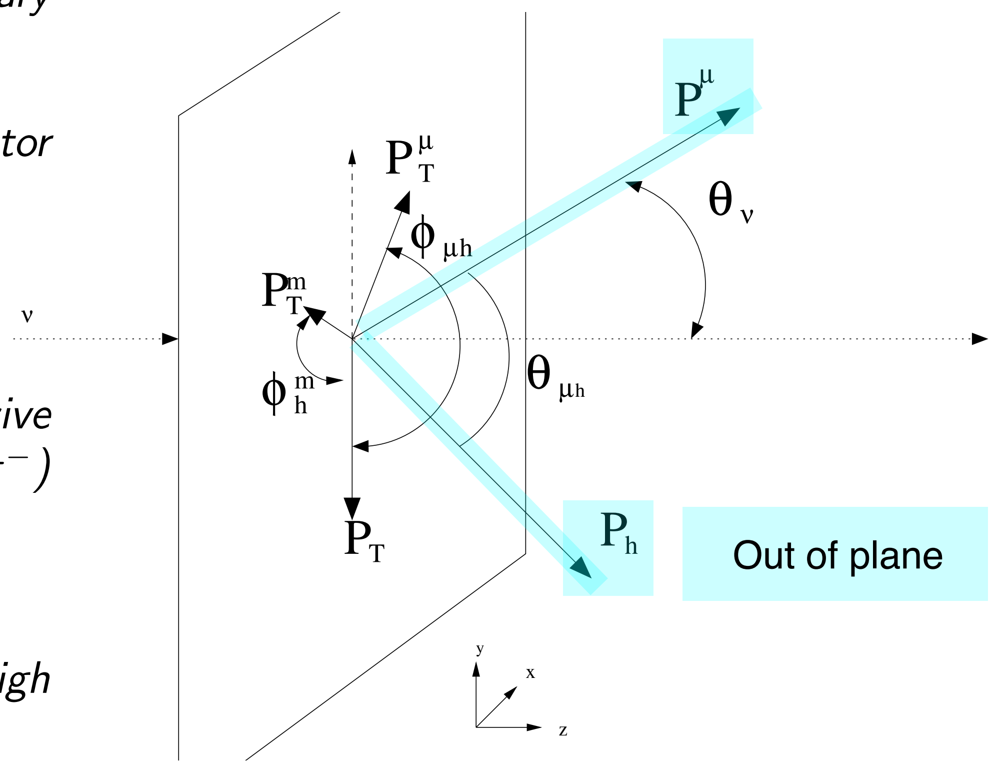
EVENT KINEMATICS & $\nu(\bar{\nu})$ ENERGY SCALES

- *High resolution on 4-momenta of visible secondary particles, $\Delta E < 0.2\%$ for charged particles*
- *Measurement of total hadron vector from vector sum of particle momenta, $\Delta E_{\rm Had} < 0.5\%$*

  $\Longrightarrow$ MISSING $\mathrm{P_T}$ *vector measurement*

  $\Longrightarrow$ *Detailed event topology*
- *Use hadron vector and missing P_T in exclusive topologies (QE 2-trk, RES 3/2-trk, Coh. π^+/π^-) to study $\nu(\bar{\nu})$ energy scale & constrain related nuclear effects (e.g. FSI)*
- *Event-by-event identification of* NC/CC *with high efficiency and purity*

  $\Longrightarrow$ *Kinematic analysis of exclusive topologies*



SHORT BASELINE PHYSICS IN LBNE/LBNF

✦ **PRECISION MEASUREMENTS**: *(LBNE Collaboration, arXiv:1307.7335 [hep-ex])*

- *Measurement of $\sin^2\theta_W$ and electroweak physics;*
- *Measurement of strange sea contribution to the nucleon spin Δs;*
- *Precision tests of isospin symmetry;*
- *Precision tests of the structure of the weak current: PCAC, CVC;*
- *Adler sum rule;*
- *Studies of QCD and hadron structure of nucleons and nuclei;*
- *Strange sea and charm production;*
- *Measurement of Nuclear effects in neutrino interactions;*
- *Precision measurements of cross-sections and particle production; etc. .....*

Deep synergy with the LBL oscillation program: same requirements and mutual feedback

✦ **SEARCHES FOR NEW PHYSICS**:

- *Search for weakly interacting massive particles (e.g. νMSM sterile neutrinos);*
- *Search for high Δm^2 neutrino oscillations (e.g. LSND, MiniBooNE)*
- *Search for light (sub-GeV) Dark Matter; etc. .....*

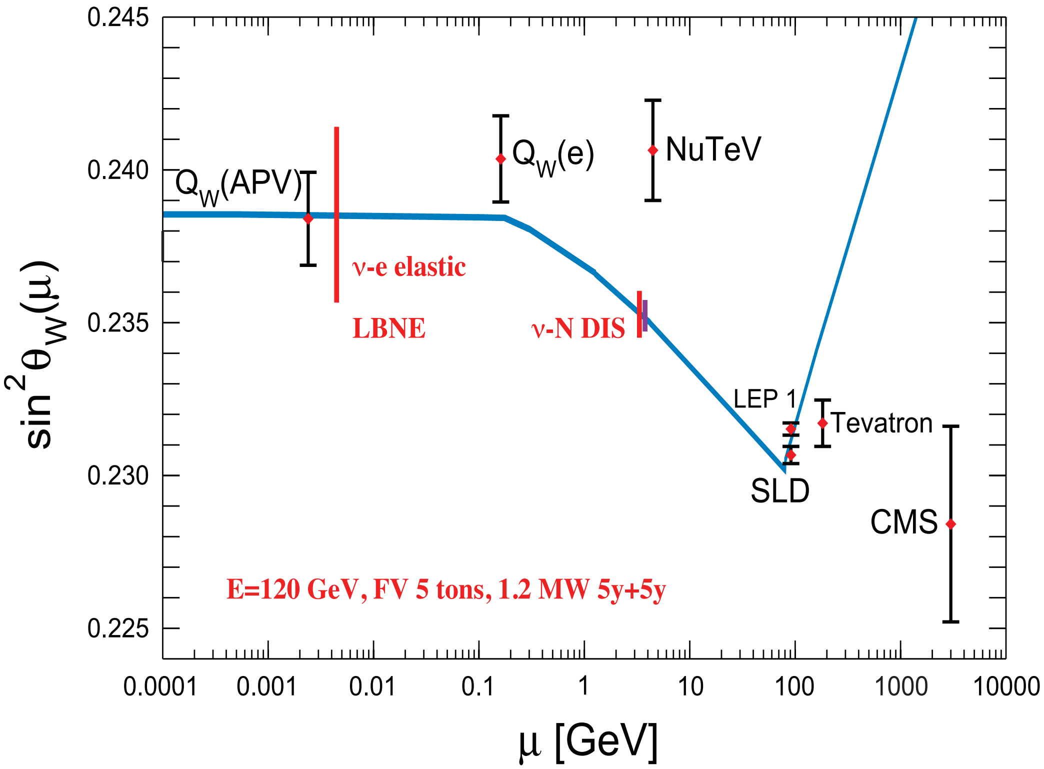
$\Longrightarrow$ *The combination of high resolution and unprecedented statistics ($\times 100$) may led to discoveries of new physics in fundamental interactions / structure of matter!*

$\Longrightarrow$ *More than 200 physics papers and > 100 Ph.D. thesis expected*

PRECISION ELECTROWEAK MEASUREMENTS

✦ *Sensitivity from ν scattering in LBNE/LBNF comparable to the Collider precision:*

- *FIRST single experiment to directly check the running of $\sin^2\theta_W$:*
  elastic ν-e scattering and νN DIS have different scales
- *Different scale of momentum transfer with respect to LEP/SLD (off Z^0 pole)*
- *Direct measurement of neutrino couplings to Z^0*
  $\Longrightarrow$ *Only other measurement LEP $\Gamma_{\nu\nu}$*
- *Independent cross-check of the NuTeV $\sin^2\theta_W$ anomaly ($\sim 3\sigma$ in ν data) in a similar Q^2 range*



✦ *Different independent channels:*

- $\mathcal{R}^\nu = \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}}$ *in ν-N DIS (∼0.35%)*
- $\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm NC}}$ *in ν-e^- NC elastic (∼1%)*
- *NC/CC ratio $(\nu p \to \nu p)/(\nu n \to \mu^- p)$*
  in (quasi)-elastic interactions
- *NC/CC ratio ρ^0/ρ^+ in coherent processes*

$\Longrightarrow$ *Combined EW fits like LEP*

✦ *Reduction of uncertainties to $\sim 0.2\%$ with 1-2 yr run in high energy mode*

FLUX MEASUREMENTS

✦ **ABSOLUTE FLUXES**

NC elastic scattering $\nu_\mu + e^- \to \nu_\mu + e^-$

$\Longrightarrow$ *Expect a* $\sim 2\%$ *precision in the absolute flux for* $0.5 \leq E_\nu \leq 10$ *GeV*

CC Inverse Muon Decay $\nu_\mu + e^- \to \nu_e + \mu$

$\Longrightarrow$ *Expect a* $\sim 2.5\%$ *precision in the absolute flux for* $E_\nu \geq 11$ *GeV*

Using quasi-elastic CC scattering off free proton (hydrogen) target $\bar{\nu}_\mu + p \to \mu + n$

$\Longrightarrow$ *Estimate a* $\sim 3\%$ *precision in the absolute flux for* $0.5 \leq E_\nu \leq 20$ *GeV*

✦ **RELATIVE FLUXES**

Use low-ν_0 *method to extract parent meson distributions and predict FD/ND*

$\Longrightarrow$ *Expect FD/ND to* $\sim$ *1-2% in fluxes vs.* E_ν *(bin-to-bin) for* $0.5 \leq E_\nu \leq 20$ *GeV*

Use coherent $\pi^\pm$ *production to determine* $\bar{\nu}/\nu$ *flux ratio*

$\Longrightarrow$ *Expect* $\sim 1\%$ *precision on the flux ratio*

PRECISION TESTS OF THE ADLER SUM RULE

- *High statistics event samples on H target from the subtraction between* $(C_3H_6)_n$ *radiators and the C target allow high precision tests of the Adler sum rule*

- *The Adler integral provides the* **ISOSPIN** *of the target:*

$$S_A = \int_0^1 \frac{dx}{2x} \left(F_2^{\bar{\nu}p} - F_2^{\nu p} \right) = I_z$$

  - *Exact sum rule from current algebra;*
  - *At large* Q^2 *(quarks) sensitive to* $(s - \bar{s})$ *asymmetry, isospin violations;*
  - *At low* Q^2 *cancellation QE, Res, DIS;*
  - *Only measurement from BEBC with 5,000 (9,000)* $\nu(\bar{\nu})$ *events on H (Z.Phys.C28 (1985) 321).*
  - *Expect* $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)$ $\nu(\bar{\nu})$ *CC interactions on free proton*

$\Longrightarrow$ *A measurement on H at the percent level at LBNF could bring to discoveries!*

- *Interesting to measure the Adler sum rule in nuclei* $S_A = (Z - N)/A$ *like C, Ca and Ar to test possible isospin violations or flavor dependencies of nuclear effects*

TESTS OF ISOSPIN (CHARGE) SYMMETRY

✦ *Experimental check of isospin symmetry in nucleon, $u_{p(n)} \neq d_{n(p)}$. Fine grained ND in LBNE/LBNF with ν AND $\bar{\nu}$ on isoscalar* C TARGET *:*

$$\frac{F_2^{\nu C}}{F_2^{\bar{\nu} C}}(x, Q^2) - 1$$

- *Structure function ratio reduces systematic uncertainties;*
- *Need to take into account charm quark effects $\propto \sin^2 \theta_C$. Sensitivity to m_c;*
- *A non-vanishing strange sea asymmetry $s(x) - \bar{s}(x)$ would affect the result. Need combined analysis with charm production in ν and $\bar{\nu}$ interactions;*
- *Potential effect of nuclear environment e.g. with Coulomb field.*

✦ *Collect ν and $\bar{\nu}$ interactions on both* Ca AND Ar TARGETS *to disentangle nuclear effects from isospin effects in nucleon structure functions.*

- *Measure ratios $F_2^{\nu A}/F_2^{\bar{\nu} A}(x, Q^2)$;*
- *Use heavier isoscalar target, $^{40}_{20}$Ca, to verify nuclear effects in $^{12}_{6}$C;*
- *Use second target with isovector component but same A as Ca: $^{40}_{18}$Ar.*

MEASUREMENT OF Δs

✦ NC ELASTIC SCATTERING *neutrino-nucleus is sensitive to the strange quark contribution to nucleon spin, Δs, through axial-vector form factor G_1:*

$$G_1 = \left[-\frac{G_A}{2}\tau_z + \frac{G_A^s}{2} \right]$$

At $Q^2 \to 0$ we have $d\sigma/dQ^2 \propto G_1^2$ and the strange axial form factor $G_A^s \to \Delta s$.

✦ *Measure* NC/CC RATIOS *as a function of Q^2 to reduce systematics ($\sin^2\theta_W$ as well):*

$$R_\nu = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}; \qquad R_{\bar{\nu}} = \frac{\sigma(\bar{\nu} p \to \bar{\nu} p)}{\sigma(\bar{\nu} p \to \mu^+ n)}$$

- *Statistical precison in LBNE/LBNF ND will be at the 10^{-3} level: $\sim$ 2.0 (1.2) $\times 10^6$ ν $(\bar{\nu})$ NC events (best measurement BNL E734 with 951 (776) $\nu(\bar{\nu})$ NC events, PRD 35 (1987) 785);*
- *A precision measurement over an extended Q^2 range reduces systematic uncertainties from the Q^2 dependence of vector ($F_{1,2}^s$) and axial (G_A^s) strange form factors;*
- *Need to check background subtraction (e.g. neutrons etc.);*

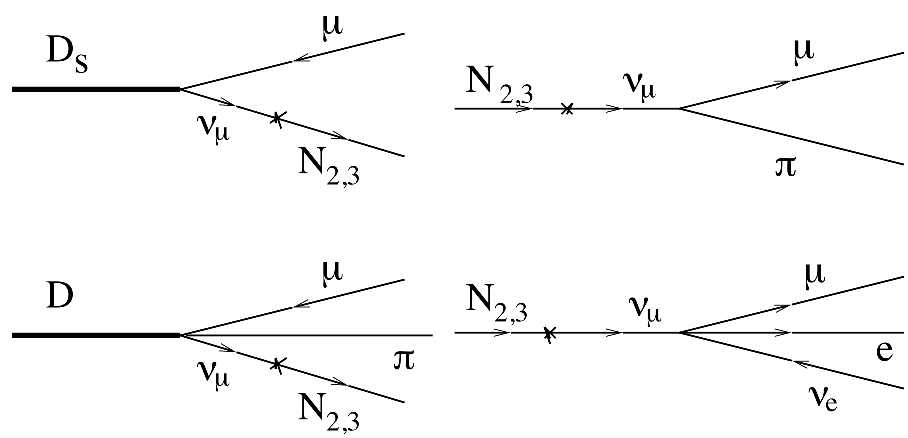
SEARCH FOR NEUTRAL LEPTONS

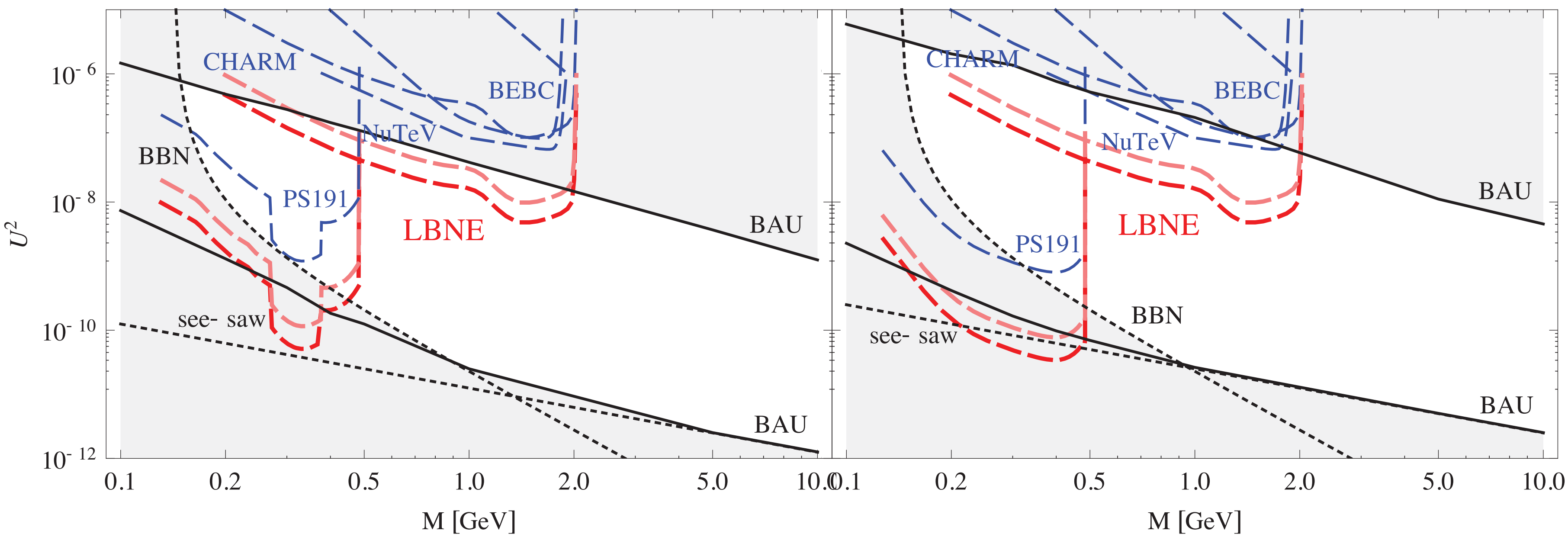
✦ *νMSM with 3 sterile RH neutrinos N_1, N_2, N_3:*

(T. Asaka and M. Shaposhnikov, PLB 620 (2005) 17)

- *N_1 with very large lifetime and $m(N_1) \sim 10$ keV;*
- *N_2, N_3 almost degenerate $m \sim 100$ MeV-few GeV*

$\Longrightarrow$ *Search for weak decays*
$e^+e^-\nu, \mu e\nu, \mu^+\mu^-\nu, e^-\pi^+, \mu^-\pi^+$, etc.





SUMMARY

- *High resolution – low density ($\rho \sim 0.1$ g/cm^3) & magnetized (B=0.4T) – near detector important to constrain systematics in LBNE/LBNF and fully achieve physics potential of long-baseline oscillation analyses*

- *Multiple nuclear targets in LBNE/LBNF ND will provide a rich Short Baseline physics program, characterized by a deep synergy with long-baseline oscillation analyses, offering a generational advance in precision measurements and searches*

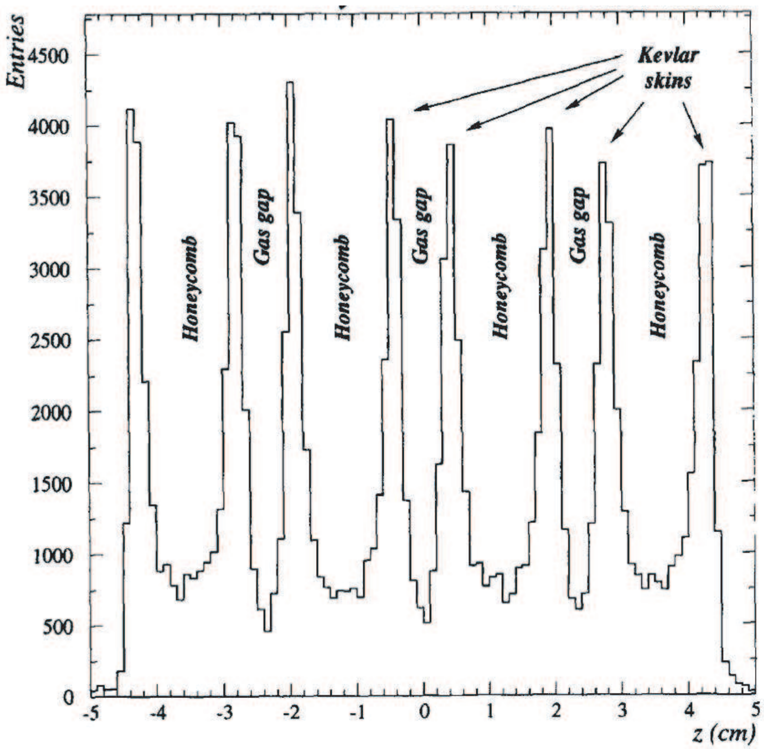
  $\Longrightarrow$ *Discovery potential within short-baseline physics*

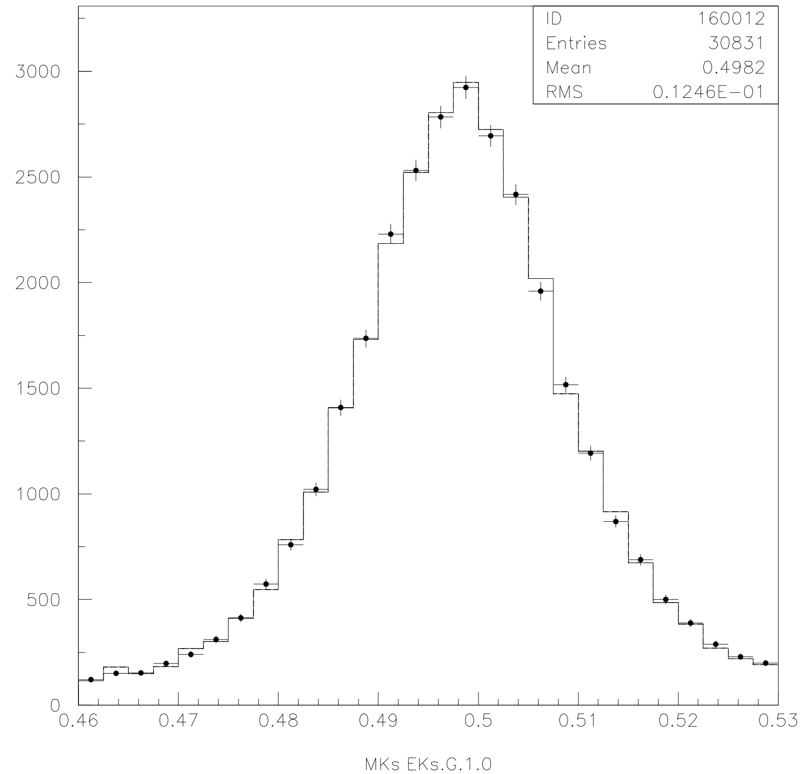
- *The availability of unprecedented neutrino fluxes at LBNF, coupled with a high resolution near detector, can elevate neutrino physics to the same level of precision of e+e physics (LEP/SLD)*

  $\Longrightarrow$ *Sensitivities comparable with other complementary dedicated programs*
  $\Longrightarrow$ *Exploit the uniqueness of the (anti)neutrino probe*

Backup slides

VERTEX RESOLUTION AND ENERGY SCALES





Neutrino radiography of one drift chamber

Reconstructed K^0 mass

- *NOMAD: charged track momentum scale known to $< 0.2\%$*
  hardonic energy scale known to $< 0.5\%$
- *DUNE ND: $\sim$ 100 $\times$ more statistics and 12 $\times$ higher segmentation*

Source of uncertainty	$\delta R^{\nu}/R^{\nu}$		Comments
	NuTeV	LBNE	
Data statistics	0.00176	0.00074	
Monte Carlo statistics	0.00015		
Total Statistics	*0.00176*	*0.00074*	
$\nu_e, \overline{\nu}_e$ **flux** ($\sim 1.7\%$)	0.00064	0.00010	e^-/e^+ identification
Energy measurement	0.00038	0.00040	
Shower length model	0.00054	n.a.	
Counter efficiency, noise	0.00036	n.a.	
Interaction vertex	0.00056	n.a.	
$\overline{\nu}_\mu$ **flux**	n.a.	0.00070	Large $\bar{\nu}$ contamination
Kinematic selection	n.a.	0.00060	Kinematic identification of NC
Experimental systematics	*0.00112*	*0.00102*	
d,s→c, s-sea	0.00227	0.00140	Based on existing knowledge
Charm sea	0.00013	n.a.	
$r = \sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00018	n.a.	
Radiative corrections	0.00013	0.00013	
Non-isoscalar target	0.00010	N.A.	
Higher twists	0.00031	0.00070	Lower Q^2 values
R_L (F_2, F_T, xF_3)	0.00115	0.00140	Lower Q^2 values
Nuclear correction		0.00020	
Model systematics	*0.00258*	*0.00212*	
Total	**0.00332**	**0.00247**	